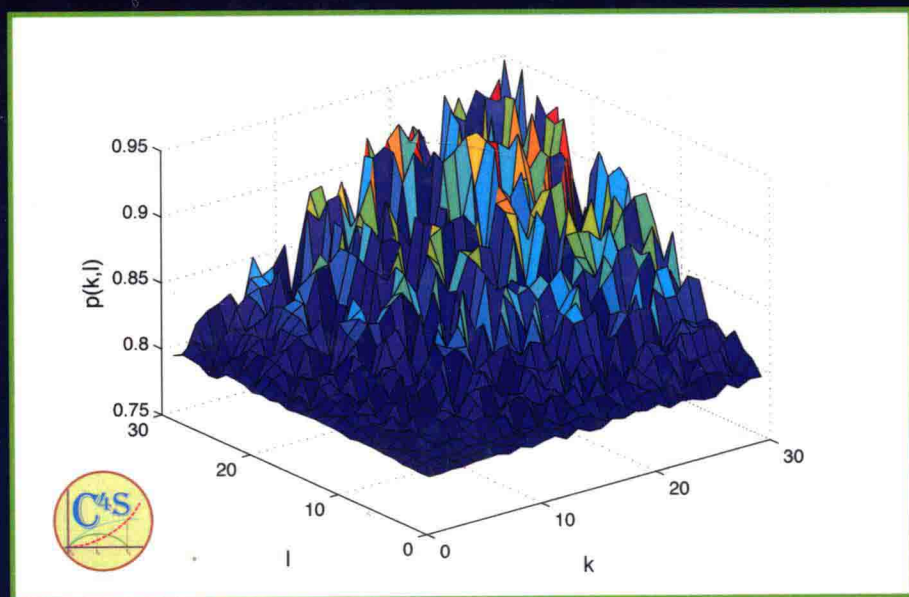


## ENGINEERING SYSTEMS AND SUSTAINABILITY SERIES

Series Editor: Ganti Prasada Rao

Co-Editors: Heinz Unbehauen, D. Subbaram Naidu, Hugues Garnier, and Zidong Wang



# **Nonlinear Stochastic Control and Filtering** *with* **Engineering-Oriented Complexities**

Guoliang Wei, Zidong Wang, and Wei Qian



CRC Press  
Taylor & Francis Group

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**Guoliang Wei  
Zidong Wang  
Wei Qian**



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## **ENGINEERING SYSTEMS AND SUSTAINABILITY SERIES**

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# Symbols

## Symbol Description

|                                                                    |                                                                                                                                                                                                                                                             |                           |                                                                                         |
|--------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|-----------------------------------------------------------------------------------------|
| $\mathbb{R}^n$                                                     | The $n$ -dimensional Euclidean space.                                                                                                                                                                                                                       |                           |                                                                                         |
| $\mathbb{Z}$                                                       | The set of integers.                                                                                                                                                                                                                                        | $Pr\{\cdot\}$             | The occurrence probability of the event “.”.                                            |
| $\mathbb{Z}^+(\mathbb{Z}^-)$                                       | The set of nonnegative (negative) integers.                                                                                                                                                                                                                 | $\mathbb{E}\{x\}$         | The expectation of stochastic variable $x$ .                                            |
| $ \cdot $                                                          | The Euclidean norm in $\mathbb{R}^n$ .                                                                                                                                                                                                                      | $\mathbb{E}\{x y\}$       | The expectation of $x$ conditional on $y$ , $x$ , and $y$ are all stochastic variables. |
| $L_2[0, \infty)$                                                   | The space of square-integrable vector functions over $[0, \infty)$ .                                                                                                                                                                                        | $\otimes$                 | The Kronecker product of matrices.                                                      |
| $\ \cdot\ _2$                                                      | The usual $L_2[0, \infty)$ norm.                                                                                                                                                                                                                            | $\mathbb{R}^{n \times m}$ | The set of all $n \times m$ real matrices.                                              |
| $C([-\tau, 0]; \mathbb{R}^n)$                                      | The family of continuous functions $\phi$ from $[-\tau, 0]$ to $\mathbb{R}^n$ with the norm $\ \phi\  = \sup_{-\tau \leq \theta \leq 0}  \phi(\theta) $ .                                                                                                   | $I$                       | The identity matrix of compatible dimension.                                            |
| $(\Omega, \mathcal{F}, \{\mathcal{F}_t\}_{t \geq 0}, \mathcal{P})$ | The complete probability space with a filtration $\{\mathcal{F}_t\}_{t \geq 0}$ satisfying the usual conditions (i.e., the filtration contains all $P$ -null sets and is right continuous).                                                                 | $X > Y$                   | The $X - Y$ is positive definite, where $X$ and $Y$ are symmetric matrices.             |
| $L^p_{\mathcal{F}_t}([-\tau, 0]; \mathbb{R}^n)$                    | The family of all $\mathcal{F}_t$ -measurable $C([-\tau, 0]; \mathbb{R}^n)$ -valued random variables $\xi = \{\xi(\theta) : -\tau \leq \theta \leq 0\}$ , such that $\sup_{-\tau \leq \theta \leq 0} \mathbb{E} \xi(\theta) ^p < \infty$ , for $t \geq 0$ . | $X \geq Y$                | The $X - Y$ is positive semi-definite, where $X$ and $Y$ are symmetric matrices.        |
| $\omega(t)$                                                        | $m$ -dimension Brownian motion defined on a com-                                                                                                                                                                                                            | $M^T$                     | The transpose matrix of $M$ .                                                           |
|                                                                    |                                                                                                                                                                                                                                                             | $\lambda_{\max}(M)$       | The maximum eigenvalue of $M$ , when $M$ is symmetric.                                  |
|                                                                    |                                                                                                                                                                                                                                                             | $\lambda_{\min}(M)$       | The minimum eigenvalue of $M$ , when $M$ is symmetric.                                  |
|                                                                    |                                                                                                                                                                                                                                                             | $\ M\ $                   | The spectral norm of $M$ .                                                              |
|                                                                    |                                                                                                                                                                                                                                                             | $\text{diag}_q\{\star\}$  | $\text{diag}\{\star, \dots, \star\}$ with $q$ blocks of $\star$ .                       |
|                                                                    |                                                                                                                                                                                                                                                             | $*$                       | The ellipsis for terms induced by symmetry, in symmetric block matrices.                |

|                                                         |                                                                                     |                                                                                                                                                                                  |
|---------------------------------------------------------|-------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\text{diag}\{M_1, ..., M_n\}$                          | The block diagonal matrix with diagonal blocks being the matrices $M_1, ..., M_n$ . | matrix whose all nonzero blocks are the $i_1j_1$ th block $M_1$ , the $i_2j_2$ th block $M_2, ...,$ the $i_rj_r$ th block $M_r$ , and <i>all other</i> blocks are zero matrices. |
| $\mathfrak{M}_n[(M_1)_{i_1,j_1}, ..., (M_r)_{i_r,j_r}]$ | The $n$ th-order block square                                                       |                                                                                                                                                                                  |

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## ***Series Editor Foreword***

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Professor Andrew P. Sage of George Mason University, USA, my friend, colleague and collaborator for many decades, and also as a co-editor of this series, was a renowned scholar in the fields of systems, control, and estimation. His passing in October 2014 has been a great loss to all of us in the academic community. I remain grateful to him for his cooperation and advice. Professor Zidong Wang of Brunel University agreed to join as an honorary co-editor. I thank all the co-editors and Gagandeep Singh of CRC Press for their support.

### **This book**

Human-engineered systems develop through technological innovations and designs towards meeting both growing human needs and challenges of associated complexities. In the context of man-made systems of control nonlinearities and uncertainties enter in many ways. Complexities such as time delays, jump parameters, nonlinearities, sensor faults and parameter uncertainties, etc. are ubiquitous. These have been tackled through various methods in the past several decades and the literature related to them is vast. The emerging complexities such as randomly occurring incomplete information implying missing measurements, randomly occurring nonlinearities, and coupling delays have been the focus of attention of control and signal processing communities in order to ensure the stability and reliability of the systems. The authors of this volume have devoted much time on these aspects and published significant results. They have tried to put together the state-of-the-art methods in this book dealing with the phenomena of engineering-oriented complexities both traditional and the newly emerging from a nonlinear stochastic control perspective.

***Ganti Prasada Rao***

Series Editor

**Engineering Systems and Sustainability**

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## Series Editor

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**GANTI PRASADA RAO** earned a BE degree in electrical engineering from Andhra University, India in 1963, MTech (control systems engineering) and PhD degrees in electrical engineering in 1965 and 1970 respectively, both from the Indian Institute of Technology (IIT), Kharagpur, India. From July 1969 to October 1971, he was with the Department of Electrical Engineering, PSG College of Technology, Coimbatore, India as an assistant professor. In October 1971, he joined the Department of Electrical Engineering, IIT Kharagpur as an assistant professor and was a professor there from May 1978 to June 1997. From May 1978 to August 1980, he was the chairman of the Curriculum Development Cell (electrical engineering) established by the Government of India at IIT Kharagpur. From October 1975 to July 1976, he was with the Control Systems Centre, University of Manchester Institute of Science and Technology (UMIST), Manchester, England, as a Commonwealth Post-doctoral Research Fellow. During 1982–1983, 1985, 1991, 2003, 2004, 2007, and 2009, he visited the Lehrstuhl für Elektrische Steuerung und Regelung, Ruhr-Universität Bochum, Germany as a Research Fellow of the Alexander von Humboldt Foundation. He visited the Fraunhofer Institut für Rechnerarchitektur und Softwaretechnik (FIRST) Berlin, in 2003, 2004, 2007 2009, and 2011. He was a visiting professor in 2003 at University Henri Poincare, Nancy, France, and Royal Society-sponsored visiting professor at Brunel University, UK in 2007. During 1992–1996 he was scientific advisor to the Directorate of Power and Desalination Plants, Water and Electricity Department, Government of Abu Dhabi and the International Foundation for Water Science and Technology where he worked in the field of desalination plant control. He is presently a member of the UNESCO-EOLSS Joint Committee.

Dr. Rao has authored/coauthored four books: *Piecewise Constant Orthogonal Functions and Their Applications to Systems and Control*, *Identification of Continuous Dynamical Systems—The Poisson Moment Functional (PMF) Approach* (with D.C. Saha), *Generalised Hybrid Orthogonal Functions and Their Applications in Systems and Control* (with A. Patra) all the three published by Springer in 1983, 1983 and 1996 respectively, and *Identification of Continuous Systems* (with H. Unbehauen) published by North Holland in 1987. He is co-editor (with N.K. Sinha) of *Identification of Continuous Systems - Methodology and Computer Implementation*, Kluwer, 1991. He has authored/coauthored over 150 research papers.

He has been on the editorial boards of *International Journal of Modeling and Simulation*, *Control Theory and Advanced Technology (C-TAT)*, *Systems*

*Science* (Poland), *Systems Analysis Modeling and Simulation* (SAMS), *International Journal of Advances in Systems Science and Applications* (IJASSA) and *The Students' Journal of IETE* (India). He was guest editor of three special issues: one of *C-TAT on Identification and Adaptive Control – Continuous Time Approaches*, Vol. 9, No. 1, March 1993, and *The Students' Journal of IETE on Control*, Vols. I&II, 1992–93, *System Science*, *Special Issue dedicated to Z. Bubnicki*, Volume 33, No. 3, 2007. He organized several invited sessions in IFAC Symposia on Identification and System Parameter Estimation, 1988, 1991, 1994, and the World Congress 1993. He was a member of the International Program Committees of these symposia during 1988–1997. He was a member of the IFAC Technical Committee on Modelling, Identification and Signal Processing in 1996, and was chairman of the Technical Committee of the 1989 National Systems Conference in India. He is co-editor (with Achim Sydow) of the book series “Numerical Insights Series” published by Taylor & Francis. He is a member of the International Advisory Boards of the International Institute of General Systems Science (IGSS), *Systems Science Journal* (Poland) and International Congresses of World Organisation of the Systems and Cybernetics (WOSC).

Since 1996, Prof. Rao has been closely associated with the development of the *Encyclopedia of Desalination and Water Resources* (DESWARE) ([www.desware.net](http://www.desware.net)) and *Encyclopedia of Life Support Systems* (EOLSS), developed under the auspices of the UNESCO ([www.eolss.net](http://www.eolss.net)).

He earned several academic awards including the IIT Kharagpur Silver Jubilee Research Award 1985, The Systems Society of India Award 1989, International Desalination Association Best Paper Award 1995, and Honorary Professorship of the East China University of Science and Technology, Shanghai. He was elected to fellowship of the IEEE with the citation ‘FOR DEVELOPMENT OF CONTINUOUS TIME IDENTIFICATION TECHNIQUES’. The International Foundation for Water Science and Technology has established the ‘Systems and Information Laboratory’ in the Electrical Engineering Department at the Indian Institute of Technology, Kharagpur, in his honor.

He is listed in several biographical volumes and is a Life Fellow of The Institution of Engineers (India), Life Member Systems Society of India, Indian Society for Technical Education, Fellow of The Institution of Electronics and Telecommunication Engineers (India), Life Fellow of IEEE (USA) and a Fellow of the Indian National Academy of Engineering.

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# Preface

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Engineering-oriented complexities exist everywhere, including time delays, Markovian jump parameters, nonlinearities, sensor faults, and parameter uncertainties, etc. These complexities have been studied for several decades and could be referred to as the traditional engineer-oriented complexities. Recently, a class of newly emerged engineering-oriented complexities, i.e., randomly occurring incomplete information (such as missing measurements, randomly occurring nonlinearities, randomly occurring coupling delays, etc.), has gained some initial research interest in various communities, such as signal processing and control engineering. It should be mentioned that the occurrence of the engineering-oriented complexities inevitably affects system performance and may even lead to instability of controlled systems. So far, the analysis issues of linear systems with engineering-oriented complexities have attracted quite a lot research attention. However, the corresponding research on nonlinear stochastic systems with engineering-oriented complexities has not been fully investigated. Therefore, a seemingly important research problem is to develop new approaches addressing the analysis and synthesis problems for nonlinear stochastic systems with engineering-oriented complexities.

In this book, we focus on the phenomena of the engineering-oriented complexities, including the traditional engineer-oriented complexities and newly emerged engineering-oriented complexities from a nonlinear stochastic control perspective. The content of this book is conceptually divided mainly into three parts. In the early chapters of the book, a series of control and filtering approaches, especially robust control/filtering methods, is introduced for stochastic systems with traditional engineer-oriented complexities. Furthermore, some sufficient conditions for the existence of the desired controllers and filters are given by verifying the feasibility of the corresponding linear matrix inequalities or Hamilton–Jacobi inequalities. In the bulk of the book, the incomplete information with varying occurring probabilities is first introduced to represent a new complexity that belongs to the newly emerged engineering-oriented complexities. Accordingly, a probability-dependent gain-scheduling approach is proposed to design the filters and controllers. In the final chapters of the book, both the theory and methodology developed in previous parts are employed to deal with the state estimation/filtering problems for networked control systems, genetic regulatory networks, and complex networks.

The compendious framework and description of this book are given as follows. In Chapter 1, the research background and motivation are discussed,

the research problems to be addressed in this book are proposed, and the outline of this book is given. Chapter 2 is concerned with the robust stability and stabilization problems for a class of stochastic time-delay interval systems with nonlinear disturbances. Robust stabilization and  $H_\infty$  control problems are investigated in Chapter 3 for a class of stochastic time-delay uncertain systems with Markovian switching and nonlinear disturbance. In Chapter 4, the design issues of the  $H_\infty$  state estimator and  $H_\infty$  output feedback controller are investigated for stochastic time-delay systems with nonlinear disturbances, sensor nonlinearities, and Markovian jumping parameters. Chapter 5 provides some analysis on  $H_\infty$  performance for a general class of nonlinear stochastic systems with time-delays, where the addressed systems are described by general stochastic functional differential equations. In Chapter 6, the filtering problem is studied for a class of discrete-time stochastic nonlinear time-delay systems with missing measurement and stochastic disturbances. Chapters 7, 8, and 9 consider the probability-dependent control and filtering problems for time-varying nonlinear systems with incomplete information by using the gain-scheduling technique. In Chapter 10, the filtering problem is addressed for a class of discrete-time stochastic nonlinear networked control systems with multiple random communication delays and random packet losses. The filtering problem is studied in Chapter 11 for a class of nonlinear genetic regulatory networks with state-dependent stochastic disturbances and state delays. In Chapter 12, the  $H_\infty$  state estimation problem is investigated for a class of discrete-time complex networks with probabilistic missing measurements and randomly occurring coupling delays. Based on the gain-scheduling technique, the  $H_\infty$  synchronization control problem is addressed in Chapter 13 for a class of dynamical networks with randomly varying nonlinearities.

**Guoliang Wei, Zidong Wang, and Wei Qian**  
**Authors**

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## Authors

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**Guoliang Wei** earned the BSc degree in mathematics from Henan Normal University, Xinxiang, China, in 1997, and the MSc degree in applied mathematics and the PhD degree in control engineering, both from Donghua University, Shanghai, China, in 2005 and 2008, respectively. He is currently a professor with the Department of Control Science and Engineering, University of Shanghai for Science and Technology, Shanghai, China. From March 2010 to May 2011, he was an Alexander von Humboldt research fellow in the Institute for Automatic Control and Complex Systems, University of Duisburg-Essen, Germany. From March 2009 to February 2010, he was a postdoctoral research fellow in the Department of Information Systems and Computing, Brunel University, Uxbridge, UK, sponsored by the Leverhulme Trust of the UK. From June to August 2007, he was a research assistant at the University of Hong Kong. From March to May 2008, he was a research assistant at the City University of Hong Kong. His research interests include nonlinear systems, stochastic systems, and bioinformatics. He has published more than 50 papers in refereed international journals. He is a very active reviewer for many international journals.

**Zidong Wang** is currently professor of dynamical systems and computing at Brunel University London in the United Kingdom. From January 1997 to December 1998, he was an Alexander von Humboldt research fellow with the Control Engineering Laboratory, Ruhr-University Bochum, Germany. From January 1999 to February 2001, he was a lecturer with the Department of Mathematics, University of Kaiserslautern, Germany. From March 2001 to July 2002, he was a university senior research fellow with the School of Mathematical and Information Sciences, Coventry University, UK. In August 2002, he joined the Department of Information Systems and Computing, Brunel University, UK, as a lecturer, and was then promoted to a reader in September 2003 and to a chair professor in July 2007. Professor Wang's research interests include dynamical systems, signal processing, bioinformatics, control theory and applications. He has published more than 200 papers in refereed international journals. According to the Web of Science, his publications have received more than 8000 citations (excluding self-citations) with an h-index 48. He was awarded the Humboldt research fellowship in 1996 from the Alexander von Humboldt Foundation, the JSPS research fellowship in 1998 from the Japan Society for the Promotion of Science, and the William Mong Visiting research fellowship in 2002, from the University of Hong Kong.

Professor Wang is an IEEE fellow for his contributions to networked control and complex networks. He has served or is serving as an associate editor for *IEEE Transactions on Automatic Control*, *IEEE Transactions on Neural Networks*, *IEEE Transactions on Signal Processing*, *IEEE Transactions on Systems, Man, and Cybernetics—Part C*, *IEEE Transactions on Control Systems Technology*, *Circuits, Systems & Signal Processing*, *Asian Journal of Control*, an action editor for *Neural Networks*, an editorial board member for *IET Control Theory and Applications*, *International Journal of Systems Science*, *Neurocomputing*, *International Journal of Computer Mathematics*, *International Journal of General Systems*, and an associate editor on the Conference Editorial Board for the IEEE Control Systems Society. He is a senior member of the IEEE, a fellow of the Royal Statistical Society, a member of the program committee for many international conferences, and a very active reviewer for many international journals. He was nominated as an appreciated reviewer for *IEEE Transactions on Signal Processing* in 2006–2008 and 2011, an appreciated reviewer for *IEEE Transactions on Intelligent Transportation Systems* in 2008; an outstanding reviewer for *IEEE Transactions on Automatic Control* in 2004 and for the journal *Automatica* in 2000.

**Wei Qian** earned his PhD degree in the State Key Lab of Industrial Control Technology from Zhejiang University in 2009, and he is now an associate professor at the School of Electrical Engineering and Automation in Henan Polytechnic University of China. His current research interests include time-delay systems, stochastic systems, networked control systems, etc. He has published more than 20 papers in refereed journals.

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